Paper Winding

David R. Roisum, Ph.D. - Spring 2011

920-312-8466

roisum.com

drroisum@aol.com

webhandlingblog.com

Introduction

While there are six books and hundreds of articles on winding, this chapter is a broad overview written specifically for the paper industry [1]. The primary aim is to better understand the needs of two of their fussiest types of customers: the winding machine and end-use customers such as the printing press or sheeter. Many should benefit from this discussion including process/product developers, papermakers, mechanical and electrical maintenance as well as customer service. We will see that surface winders are exceptionally intolerant to gage variation and bagginess caused in large part by the nip between the winding roll and the roll*er*, more familiarly known as a drum. The reel, duplex and two-drum winders all have nips, but the two-drum winder has three nips and all are more highly loaded than in any other industry except metals. It is not unusual to have the level of tolerable profile variation before one sees winding defects be less than what is measurable by scanners and test lab instruments [2]. Even so, the winder literate technician can infer profile problems from the physics of certain defects as well as by variation in roll hardness across the width, even if they cannot be otherwise directly measured on the sheet itself. Also, tiny changes in paper chemistry, sometimes as little as kilograms per ton, can have violent affects on winding defects, such as crepe wrinkles [3] (newspaper and LWC) or on productivity, such as speed limiting vibration or even set throws [4].

Second we will address some needs of those who must maintain and operate a paper winding machine. Here we will note that the required or at least commonly specified precisions of roller alignment and diametral profile are tighter than both upstream equipment (with the exception of headbox slice lips and nips at the press and calender) and downstream equipment such as printing presses. We will also see that the control complexity, especially with motor drives, greatly exceeds most everything found elsewhere in the paper industry. Some newer designs of reels may have as many lines of PLC and drive code than then entire pulp and paper mill complex of a decade prior. This control complexity strains the time and talents of designers, process engineering, electrical maintenance, operators and troubleshooters alike. Also, the degree of man-machine interaction is higher on winders than most other equipment in a paper mill, thus requiring a greater attention to ergonomics and safety.

Finally, we address some needs of the paper mill customer. Choices for paper properties and roll size can have huge implications on the levels of waste seen both in the paper mill as well as at the customer. At the very least we hope that the customer can recognize certain defects and know what factors conspired to make them. These factors vary from nominal paper properties to paper machine design and operation and maintenance to winder type and winder settings. However, it also extends to factors that are solely controlled by the customer such as *their* machine design and maintenance and operation. That is not to say we make a generic list of aspects of all machines in the process for a particular defect. We usually know quite specifically what few factors, usually less than a half-dozen, will make a significant difference for a specific defect. Some of these factors are requested/specified by the end-use customers themselves and agreed to by paper mill sales. With regard to customer-supplier relations we will discuss roll quality inspection and measurement. That we have troubles with winding should not be surprising. Rather, troubles should be expected. That is because paper was not designed to be wound. This delicate material was never designed to be pulled in the MD by metal cylinders weighing tens of tons or be compressed in the ZD at pressures exceeding that of an automobile tire. Instead, paper was designed to be economically made (paper machine) and to meet end-use customer requirements (such as for printing). It is fortunate that paper happens to survive the winding process, most of the time.

Winder Types Found in a Paper Mill

Winding enables papermaking as we know it because the wound roll is a convenient place to store large volumes of paper that are produced at high rates. Other paper storage options, such as folding and sheeting, are not used in paper mills and are used only by a very few of their customers in applications such as facial tissue and sheet fed presses respectively. Winders are found in several locations in paper mills. The first winder is at the end of a paper machine and is, with few exceptions, a type called a (Pope or level-rail) *reel*. The reel makes parent rolls of paper (also called logs or reels or spools) that are as wide as the paper machine and in roll diameters of around 2-3 meters. The reel is a continuous winder meaning that it can not stop during roll changes and thus transfers from one reel spool or mandrel to the next are made automatically and at speed.

A second winder type, a *rereeler*, is peculiar only to some offline coated and supercalendered papers. The windup of a rereeler, as its name might imply, is almost identical to a reel except that it does not have a primary arm or an automatic turnup. Upstream of the rereeler is an unwind and possibly trim slitters. The purpose of a rereeler is to edit out certain problems, such as holes, coming from the paper machine before they are sent through the fussy offline coater and supercalender where web breaks are costly and can damage the equipment. Also peculiar only to these same grades is a coater or *supercalender windup*. Both of these winder types are discontinuous or start-stop operations so that unwind and windup rolls are changed when the machines are stopped.

Parent rolls from the reel, rereeler or supercalender windup are obviously much too large for end-use customers and so must be cut down to smaller widths and diameters. The machine that makes these customer sized shipping rolls is properly called a *slitter rewinder,* but is commonly shortened to just '*winder'* in most mills. There are two distinctly different classes of rewinding machines used in mills; the two-drum and duplex winder. Finally, there are usually *salvage* winders that can take a single shipping sized roll and rewind it, usually with the capability of edge guiding and occasionally slitting or edge trimming. This extra processing step can be used to edit out bad material, splice together rolls to get shipping sized diameters and to correct most types of poor roll edges provided that the paper is of adequate quality. Salvage winders are also useful for trials and roll inspection. Each of these winding machines will be discussed in more detail after we discuss some basic winding theory.

Winder Classes and Types

Most winders fall into one of four *classes*. This determines which of the adjustments for winding tightness are available and to some extent the range that those adjustments can operate to effectively change wound roll tightness [5]. The adjustments are known as the TNT's of winding which stands for *Tension*, *Nip* and (center-surface wind) *Torque* (differential). Tension is web tension entering the windup as might be measured by load cells. Nip is the pressure between the winding roll and a roller (often called a drum in the paper industry). Torque is not motor torque as its name might seem to imply, but rather the difference of torque between two motors that are somehow connected to the winding roll.

The proper units for web strength in most of the web industries are lineal; in other words force per unit of web width. In the metric system this would be kN/m. In the 'English' system this would be lb/in, often expressed as PLI that stands for Pounds (of force) per Lineal Inch of web width. The proper units for winding tension, nip and torque are also force per unit width. While these web units are the usual standard for tension, many machines have uncalibrated nips (often measured as pressure on a cylinder) and motors (usually measured as amps). Air/hydraulic pressure on cylinders and motor amps are units that are peculiar to a peculiar machine so that direct comparison to other machines is not possible. A solution to this 'Tower of Babel' problem is to calibrate old machines and insist that all new machines be calibrated and calibratable (procedures given in the service manual) as specified in the purchasing contract [6].

The little 's' in the TNT's stands for speed because only some webs are speed dependent via the effects of air entrainment. Most paper grades are mildly speed dependent at paper mill speeds. Smooth materials, such as glossy magazine paper, are more speed dependent than are rough materials, such as kraft or tissue. For comparison, plastic film is extremely sensitive to air entrainment because there is little surface roughness in which to 'park' the entrained air. While we can give entrained air on rollers a 'parking place' using grooving and other techniques, wound rolls rely on surface roughness of the web as well as nonconformity of the

layers to do this. Excessive air in a wound roll can cause excessive looseness and some air bubble defects that may result in wrinkling. The nip is the primary tool for excluding air (paper) or metering air (film) into the winding roll because it is about 10X as strong as tension of an equivalent value.

Each of these control adjustments for tightness has limitations. For example, *tension* less than around 10% of the breaking strength of a material often results in web path stability problems that can be a problem in itself and/or can cause poor wound roll edge quality. Downstream in the printing press, registration may suffer if tension is reduced. Conversely, tension more than around 25% of the breaking strength can damage the web when wound or even break the web before it reaches the windup. (Sometimes tissue is 'tensioned' to nearly 50% of strength but it can be done only because it is very ductile and because it is run in draw/speed control.)

Very low *nips* are hard to control consistently and very high nips can damage the web or winding roll, especially if there are caliper profile problems. *Torque-differential* requires two motors. The sum of the two motors makes web tension and the difference of the two motors makes the 'torque' adjustment. The difference in torque between the motors can be large enough so that one of the motors is intentionally regenerating instead of motoring. In other words, they are by intention 'fighting' each other. This requires two motors, each of which must be bigger than if there were only one. Torque differential, when available, is usually motor limited. In other words, the second motor is so expensive that it is often undersized and thus the effect of torque is usually machine limited rather than web or roll limited. Very occasionally, however, excessive torque differential can cause the winding roll to slip on the drums and is thus web handling limited. To summarize; each of the TNT's might be limited at each end of its range by the web (mainly tension), the winding roll (tight or loose defects for example), the machine (design limits) or other issue.

The winder classes found in the web industries, as seen in Figure 1, are called the simple centerwind, the centerwind with layon roller, the surface winder and the center-surface winder. The centerwind has only one adjustment (aside from speed) and that is tension. Tension is available on all winder classes. The centerwind is seldom used in paper mills for many reasons including that high-speed operation requires a nip between a roller and the winding roll to reduce air entrainment to produce acceptably tight rolls. Also, the centerwind with layon roller is not common in paper mills, though it <u>is</u> the primary winder class used by the paper mill's customers. The exception is some offline coater and supercalender windups. That leaves paper mills with surface winders; such as the reel, and the center-surface winder, such as the duplex rewinder and an equivalently endowed two-drum rewinder.

Winder Classes and Types and their Affect on Wound Roll Tightness

Winder tightness can be made with any of the TNT's singly or in combination. For example, increasing tension makes the wound roll tighter as does increasing nip.

Increasing both would make an even tighter roll. Thus while the paper winder may be a 3 or 4-knob *machine*, it is only a 1-knob *process*. In other words, all these adjustments produce the same outcome; tightness. This provides extraordinary insight for the process engineer. If, for example, winding tension is giving trouble (such as web breaks), you can turn the tension down and compensate by turning the nip up and the roll may end up equivalently tight. On the other hand, if nip is giving trouble (many defects are nip-induced or nip-aggravated), then the nip can be reduced and perhaps tension and/or torque increased to compensate so that the wound roll ends up equivalently tight. Finally, if you really wanted to make a tight roll you would increase all knobs except speed, which you would want to reduce.

The first trend to be observed in the range of tightness given in Figure 2 is that, in general, the more adjustments a winder class might have, the greater the range. However, this extension in capability is primarily on the tight end. In other words, you can only make a wound roll looser by reducing the value of one or more of the *existing* adjustments rather than by adding a *new* adjustment. All adjustments, except speed, tighten the roll. The second trend is that the surface winder, ubiquitous in paper mills, has a narrower range of tightness capability. The reason the surface winder, such as the reel, is limited at the low end of tightness is simple. A certain amount of nip is required to turn the winding roll and thus making it necessarily produce a tighter roll than might a centerwinder with layon roller that does not have that limitation. Also, for reasons too theoretical to discuss here, the surface winder cannot make very tight rolls compared to an equivalently sized centerwinder with layon roller. This limitation of the tightness range of the reel is not an oversight to the extent that the reel has proven itself a most practical choice for the end of the paper machine. It is mentioned here only because the range limitation and others limitations of the paper machine reel make trying to change roll tightness somewhat limited and ineffective.

Roll Structure Theory and Control Curves

Nowhere in winding discussions is there more debate than what is the 'best control curve' for the winder. Before we address that we should make it clear that winders differ from almost any other machine in the paper industry in that control settings are not necessarily constants for a grade or run. For example, dryer temperature on a paper machine might be varied, but not quickly nor regularly. In contrast, the *tightness* of winding might be programmed to vary from tighter near the core to looser at the outside of the roll. Winder controls are usually capable of varying Tension, Nip, Torque and speed automatically over the course of the minutes of a winding cycle. Tension settings on modern paper winders *tend* to be constant with roll diameter, but are occasionally set to taper linearly from a setpoint value at the core to a slightly lower setpoint value at the outside. In converting tension is most often tapered, sometimes aggressively.

Analogous to the linear reduction of tension with roll diameter is the reduction of front drum torque split. While the total torque remains essentially constant (recall the sum of the two motors is tension plus drag), the split starts from mostly front

drum torque with the back drum possibly going into regeneration to mostly back drum with the front drum motoring very little or possibly even regenerating.

Nip controls, particularly on two-drum winders, are much more complicated and for good reasons. As seen in the bottom of Figure 3, the nip on the drums is a function of roll weight, rider roll nip loading and the geometry of the wedge angle in the drum pocket. If there were no rider roll at all, the nip would be so light at the beginning of the wind, being essentially the weight of the core (and possibly core-shaft) that the winding roll might not be able to pull web tension because the winding roll might slip on the drums. Also, the roll would be wound tighter at the end of the cycle than near the core because of the increasing large roll weight. Winding tight over loose can result in poor roll structure as we will soon see. To compensate for the increasing roll weight, a programmable rider roll loading is employed. (Exceptions are found in the rubber and textile industries that suffer from the above problems due lack of a rider roller.)

In the first half of the last century, the rider roll loading was literally all or nothing, as is common in most converting winders. The full weight of the rider roll would sit on the winding roll for the first half of the winding cycle then would be lifted off entirely for the latter half. This step change in winding nip was not very graceful and left a fault or weakness in the roll at that position. Thus for the next quarter century the rider roll nip was made to vary from big to little by simple devices such as cams and pneumatic regulators. However, since the advent of industrial computers the gold-standard is a curve where the nip load of the rider roll loading is back-calculated to achieve a constant nip of the winding roll on the drums all the way through the winding cycle. This is again seen in the bottom of Figure 3. The lower value at the beginning, before peaking and then dropping, is a result of the rapidly changing wedge angle of the small winding roll in the drum pocket. While it might seem complex, it is nothing more than high-school trigonometry.

So back to the questions of "what is the best curve" and "why all this complexity of controllers" that can vary any or all of the TNT's automatically with roll diameter? One reason is termed *roll structure* or equivalently *taper* in the converting industry. Either means to start tight at the core, finish looser at the outside of the roll and, perhaps most importantly, vary the tightness smoothly as the roll builds from the core to the outside. By smoothly we mean no upsets or sudden changes. The reason is that abrupt changes in any of the TNT's can risk an increase in certain roll defects such as one type of star and the most common type of telescope. (These and other common defects will be discussed later). Thus winding people learned that 'curves' can improve winding in some cases.

Unfortunately, the web industries learned roll structure lesson too well because it led to a widespread fallacy of the general rule. That is, most or all defects could be improved by proper attention to roll structure. While it is true that the incidence and severity of *some* defects can be reduced by winder controls, many or even most defects are largely insensitive to control settings. Examples include those defects directly caused by caliper (gage or thickness profile) variation as well as some due

to maintenance (such as wrinkles due to misalignment) or operation (such as setting the wrong distance between the slitter to yield the wrong roll width). Another major problem with the widespread fallacy of the power of the 'best curve' is that the best curve, when it does help with a particular defect, is different for each type of defect. Thus, for example, the best curve is quite different for the telescope (where tight start is important) than for crepe wrinkles at the outside of a roll (where a low rider roll nip is important). In the next section we will describe what we mean by tightness and how might we measure it. Wound roll tightness is, after all, the point of all of this TNT complexity and a large factor in certain defects.

Tightness and Roll Quality Measurement

The word *tightness* has been used up to this point for a specific reason. It was to avoid attachment to any particular alias or synonym that is too specific. A perfect example here is that in the paper industry the nearly synonymous and much more commonly used description of a wound roll condition is *hardness*. The reasons are both historical and practical. The first estimates of the tightness of the roll were made by manually striking and sounding a roll with a stick or a club. Certainly this method is fast and cheap and is still used today in almost every mill. This method can also be good because roll quality, defined by a reduced risk for certain defects, often corresponds to hardness as determined by the sound and feel of the rebound of the stick. If the roll sounded soft, it was probably looser there and risked a certain subset of defects. If the roll sounded hard, it was probably tighter there and risked a different subset of defects. If the roll had varying hardness across the width of a roll, yet another subset of defects might be seen. In the first two cases the cause may be winder related. In the last the cause would most be likely a variation of caliper/density/thickness across the web, sometimes referred to as profile. It is convenient to break defects, which will be covered later, into classes of tight defects, loose defects, roll structure defects, profile defects and maintenance/operation defects. In any case, the stick is a way to most simply estimate tightness.

So for most of the last century in the paper industry, the primary measure of tightness and thus the propensity to certain defects was roll hardness as estimated by an operator striking the parent roll or shipping roll with a club. However, this measure is subjective and thus limited for any number of reasons. The first quantification of roll hardness was either the Schmidt Concrete Hammer or the Beloit Rhometer, both gaining widespread acceptance beginning in the 1970's and still continuing to today. These instruments have been found to be so trustworthy that a few mills internally reject (repulp) some of their rolls solely based on hardness measurements. Usually the rolls are rejected on the basis of excessive hardness variation across/within a single finished shipping roll rather than exceeding a maximum or minimum value. Statistical evidence has been shown that variation of hardness across a roll is correlated to certain defects, such as corrugations, and well as runnability (web break rate in printing).

It is interesting to note that the film industry had also found that Schmidt Hammer and Beloit Rhometer measurements correlated well to certain roll defects. The only

major difference in the industries was that while in the paper industry it was the *supplier* that culled rolls, in the film industry it was usually the *buyer* that wrote hardness specifications into their purchasing contract, often as a response to previous problems. While both devices still continue to enjoy widespread use, usually for troubleshooting rather than routine quality control screening, modern competing hardness instruments are replacing them. Two of note are the Parotester by Proceq and the RQP by Tapio.

You would think that four measures of roll hardness would be enough. However, there are limitations. In the film industry, for example, hardness only seems to correlate with defects perhaps only half of the time and those impact-based instruments can be destructive on tender webs by permanently marking the roll. Even in the paper industry the correlation of hardness can be poor, to the point of sometimes being useless, for very soft products, such as tissue, and very thick products, such as board. The reason here is easier to understand; very soft and very hard wound roll products are at the extreme ends of the measurement scales of these instruments. Another complication is that the science of winding began to show that hardness readings were not only affected by winding tightness and gage variation, but the readings were also by the grade itself. For example, two rolls could measure equally hard but be of different tightness because the material properties of the two could be different; even if they were nominally the same material otherwise, such as 30 gsm newsprint. Thus the effort to define a more independent and scientific measure of tightness led to stresses inside the roll, the subject of the next section.

To make a really long story short, there are now about a dozen measures of tightness in commercial use. These are listed in Table 1 and are categorized by their principle of operation. The reader who needs a complete treatment of these and other related subjects must have the book Winding: Machines, Mechanics and Measurements because the last third is devoted to wound roll measurements. It should be sufficient here to summarize that all of the measures are looking at the same basic phenomenon and they are all interchangeable. This is analogous to temperature that has at least five common scales (Centigrade, Rankin etc) of measure and scores of related quantitative expressions (wavelength of peak intensity of incandescent objects, mean free path of a molecule, etc). The major difference between winding and temperature is that there are no simple equations to convert one winding scale or measure to another. While it is possible to experimentally make a conversion chart between any two wound roll measures, it would be valid for only a very specific grade or material. Thus the practical approach in the paper mill is to find a measure that is easy to use and is sensitive enough for judging roll quality.

Finally a note on another widespread fallacy. That is winding tightness is a reflection solely of winder design and winder settings and paper grade. It is true that the increasing any of the TNT's will increase the tightness of the roll. However, what is changed here is ONLY the *average* tightness of the roll across the width. The

distribution of tightness across the width a single roll is determined by caliper/gage/thickness variation. A single roll that is tight on one end is thicker there than on the other side that is loose. In the film industry, the variation of tightness (by any related measure) due to web thickness variation can greatly exceed the variation of tightness possible due to practical changes in winder settings. In paper we see the same thing where pressures/stresses on one side of the wound roll might literally be zero, evidenced because you can fan the layers with your finger, while the other side must be tight or quite tight. Situations like this seldom have any noticeable remedy by changing winder settings. The source of the profile variation has to be identified and corrected.

Table 1 – Roll Quality Measures

- Process
  - TNT Settings and Machine
- Stresses-Strains
  - Wound-In-Tension
  - Radial Stress Distribution
  - Tangential Stress Distribution
  - Strains
  - Displacements
  - Geometry
  - Bulk
  - Density
  - Diameter and Length
  - Diameter, Width and Roll Weight
- Pressure Based Measurements
  - Axial Press
  - Caliper in Roll
  - Core Torque
  - Density Analyzers
  - Pressure in Roll
  - Pull Tab
- Strain Based Measures
  - Cameron Gap
  - WIT-WOT
- Non-Fundamental Roll Measures
  - Bill Club Hardness
  - Firmness (tissue and toweling)
  - Parotester
  - Rhometer
  - Roll Quality Profiler
  - Schmidt Hammer
  - Smith Needle

Winding Theory – Stresses Inside the Roll

While good roll structure is helpful for some defects in some situations, it remained only an observation, not even rising to the level of a good working theory. The reasons are primarily two. First, the concept only applied a very tiny portion of the hundred plus defects listed in the book Roll and Web Defect Terminology book, which is an encyclopedia of paper defects. Second, it was not predictive for even those few defects. The next revolutions in winding were based on empirical measurements and then modeling of stresses in wound rolls. These studies began in the 1960's and continue to the present.

There are two primary stresses inside a roll that help make sense of tightness dependant defects. These stresses, shown in Figure 4, are the pressure between the layers and the stress in the MD. Both of these types of stresses vary through the radius of the wound roll *and* vary with the history of the tightness of the roll as it is wound, which is often called roll structure. Of course, the values of these stresses at each radial position also depend on material properties. This means that some (low modulus) materials are easy to winding tight, perhaps too tight. On the other hand, paper is quite stiff so that getting sufficient tightness may be a challenge. Some properties required for model input, such as the ZD (radial or stack) modulus, are quite involved to measure. Furthermore, winding models are so complicated that for most of their half-century history only Ph.D.'s could run them or even had access to them. Only recently have two winding models become available in the public domain.

So a legitimate question can be asked as to how a science that could only be practiced by PhD's could be useful to help solve or at least understand winding defects in a paper mill? The answer is that these stress distributions have patterns that are common across all winders and web products, even web from other industries. These patterns are also shared by winders of all types and all operating settings. What these stresses allow us to do is to qualitatively describe many defects, even if they could not be quantitatively predicted with a plant-practical level of effort. This generic description is exceptionally useful for tension sensitive defects because it explains why the defects manifest themselves in certain parts of the wound roll and what factors most influence their frequency; exactly what plant-practical troubleshooters need.

As seen in Figure 5, the radial pressure varies from zero at the outside of the roll (because the outer layer has nothing above it except the atmosphere which cancels out) to medium in the middle of the roll, to perhaps a bit higher near the core. This high-medium-low z-shaped pressure curve as a function of radial position is common for all web materials, all winders and all winder settings. The only thing that changes much is the value of the radial stresses. There are many pressure dependent defects that are directly predicted by wound rolls models including blocking, bulk (caliper) loss and the most common type of telescoping.

The other stress direction, seen in Figure 4, is in the MD direction of the (paper) web. While the outside layer must be at the tightness it was wound, stresses on interior layers are changed by the addition of layers above. The net result of models and measurement is that most of the layers, except perhaps the outer 10% of the radius, are in MD compression. This precisely describes why starring (buckling) seen on the ends of some rolls rarely extends all the way to the core and all the way to the outside. Another very important defect that can be described with the MD stresses is the most common cause of baggy (cambered) web. In paper, perhaps half of all baggy web complaints are not caused because the web is *made* baggy on the paper machine (such as at moisture streaks). Rather, the web is made baggy after storage in a wound roll that has a caliper/gage/thickness profile variation across the width. The web is stretched differently and may creep into varying lengths across the width. While only half of all paper bagginess is caused in this way, almost all bagginess in film in foil is caused by caliper variation.

Current winding research centers around two areas. The first is to reduce limitations, i.e., make models more general. Early models could not accommodate air entrainment, gage variation, nips, centrifugal effects and many other real world phenomena, now they can. The second area is failure theories. What conditions will or will not cause a specific wound roll to be baggy due to stretching over bands of higher local caliper/gage/thickness? Will a specific wound roll be at risk for blocking or telescoping?

Winding Defects

The utility of analytical tools to troubleshoot winding defects varies enormously. Some defects, such as blocking and the common form of telescoping, can be predicted precisely if someone had the time and skills to get the right inputs. Other defects, such as bagginess caused by winding of web with caliper profile problems, are made very much more understandable by winding models. Yet models are still immature and are not good enough for many defects no matter how much time and effort you were willing to apply. Moreover, winding science only helps with tightness sensitive defects, perhaps about half of the types found in the paper industry. Winding science will not be helpful for operational defects, such as wrong roll width, or maintenance related defects, such as offsets caused by mechanical looseness or poor tension control.

When winding science is inadequate or otherwise unhelpful, we must then turn to experience; and we have plenty of it. Thousands of rolls produced every year in each of a thousand paper machines in the world has taught us much. We also learn from other industries that suffer from the same defects. This experience has taught us that, with few exceptions, defects can be classified into categories of tight defects, loose defects, poor roll structure (a.k.a. taper), profile defects, operational defects and design/maintenance related defects. These categories are almost mutually exclusive. Thus, for example, we cannot expect to help roll offsets caused by loose mechanicals to be improved by good roll structure or by playing with control curves.

Occasionally defects are not quite so simply classified. An example is crepe wrinkles that trouble both LWC (light weight coated) and newsprint. A crepe wrinkle *is* a loose defect, but only extremely weakly so. Rather, it is better described as a nip-induced defect that is greatly exacerbated by increasing nip loads [3]. Thus, you want to reduce nip as much as possible, even if it means decreasing roll tightness.

Many defects either correlate to or are directly caused by caliper/gage/thickness profile variation. In some cases, such as most baggy lanes, profile *is* the root cause. Caliper variation is also the root cause for one of the major types of starring. However, since caliper variation also causes a variation in roll tightness, almost *any* tightness sensitive defect could become more frequent with poor profiles even if they are not the root cause. This makes the winder troubleshooter extremely attentive to caliper variation, even if it means ignoring more traditional measures that are simply not adequately accurate. For example, the mere presence of a corrugation is enough to indict caliper variation even if the variation cannot be directly measured online (due to inadequate scanner sensitivity) or offline (due to small test lab sample sizes) [2].

The most common roll defects are given in Table 2 below using their standard or most common name. This is a small subset of the much more extensive list and treatment that can be found in Roll and Web Defect Terminology. Note that each of these defects has many synonyms in use in the industries so that one of the contributions of that book is to list all names in common usage and to suggest one as the primary.

Table 2 – Common Wound Roll Defects found in Paper Mills

Body and Edge Damage – due to roll handling
Crepe wrinkles – a nip-induced defect generated by unwinding and winding of some newsprint, SCA and LWC grades
Core Burst – generated by unwinding and core supported winding of some newsprint and LWC grades
Core, Offset – an operational problem
Core, Loose – winding loose at the start or, more commonly, winding on wet fiber cores
Corrugations – winding of a web with poor (caliper/thickness) profile
Crushed Roll (and core) – rough roll handling
Dished Roll – complex set of unrelated factors but mostly due to roll width growth on a wide two-drum winder
Interweaving – common on two drum winders with poor paper profile, poor winder controls and poor winder design/maintenance
Offset (rough roll edges) – common with poor paper profile, poor winder controls and poor winder design/maintenance
Soft/Hard Edges – where the paper has relatively low/high local caliper
Starred Edges – almost always on the low caliper side of a roll but can be caused by rough handling and/or poor roll structure.
Ridges – a local high relative caliper

Wrinkles (creases) – due to a variety of paper profile and winding machine causes
Wrong Roll Width – a problem with slitter positioning

One of the big challenges for troubleshooters is that many of our defects are outcomes rather than root causes. For example, there are three entirely different ways to crush a core, five different ways to have a telescope and seven different mechanisms for a starred roll. While management and Q/A might lump these together, the troubleshooter can not. He/she must identify the specific mechanism that caused that specific outcome in order to list options for remedy. Other communication problems are that there are several synonyms in use for a specific defect and that the same name might be used for entirely different defects. This is why Roll and Web Defect Terminology is such an essential book for everyone involved in the manufacturing, winding, converting and use of web products.

The Reel

The reel, shown in Figure 6, is a surface winder. Its primary components are a very large drum, a primary arm used to wind for a short time during roll transfers, and a secondary arm where the great majority of winding takes place. Since the reel must be a continuous winder (as opposed to the start-stop of an offline winder such as the two drum), provision must be made to transfer the winding from the nearly completed parent roll to the next bare spool sitting in the primary arms. This involves tail cutting, by air (or sometimes knife or tape for heavy materials) and then transferring the tail (usually by air nozzle) from the finishing parent roll in the secondary arms to the empty spool in the primary arms. A further step involves transferring the spool from primary arm location to secondary arm location.

While the time in the primary arms and the transfer is short, much less than a minute, the material wound on the primary arms is often damaged. One reason is that the transfer is quite bumpy as shown in the theoretical nip load versus diameter shown in Figure 7. The secondary arm has its own set of problems including the high friction of the nip load system. The friction is caused by mechanical sources such as the reel spool rolling on a dirty and scarred rail, gear sets tying the front and back arms together and many other moving parts. While winders of all classes and types endure tension and nip upsets at the top and bottom of the wound rolls, reels are exceptionally bad in this regard.

There have been at least two recent redesigns of this century old design by Beloit Corporation (now out of business) and its competitor Metso. The nip can be made more accurate by controlling the primary and secondary nip load by computer all the way through the cycle. Also, the nip can be made less variable by putting the reel spool on precision low-friction linear bearings such as found in the machine-tool industry. While achieving these goals, however, the result was computer and drive motor software complexity that exceeds what was found in an entire pulp and paper complex a decade prior. Also, as you can imagine, the new reel designs are double the cost of the traditional design.

One other design limitation of the reel has been recently found. We almost certainly have greatly undersized reel spools for certain grades [7]. For most of paper machine history, reel spool diameter had been sized based on deflection, (journal) stress and critical speed criteria. However, there had been no consideration for how much stress the weight of the parent roll caused on the paper just above the spool. The result was an increase in crepe wrinkles and other defects on some newsprint and magazine grades. Rather than change paper chemistry (primarily by friction modifiers), you could make the machine slightly more tolerant to nip-induced-defects by increasing spool diameter. Unfortunately, the increase required to not increase risk of these defects meant that spool sizes need to be double what they had been, or in other words, about 1.5m. Even so, many older paper mills have upgraded their spools and all associated spool handling equipment to save the several inches of risky paper at the bottom of the parent roll. Most new spools for the delicate grades are supplied to reflect these new understandings.

Two-Drum Winders

Two-drum winders take large parent rolls from the reel and cut them into customer sized widths and diameters. The winder gets its name because the weight of the winding roll set is born upon two drums as seen in Figure 8. However, it really should have been called a three-drum winder because a rider roller (called a pack or layon roller in other industries) sits on top of the winding roll set. Exceptions too this third roller are found in very small or very old paper winders as well as in rubber and textiles. The two-drum is composed of an unwind, a (poorly named) guide roll, slitter section, spreader and windup section. The mechanical design has varied little in more than a century with three exceptions. The first improvement, in the early 20th century, was to add a rider roller to better control the nip. The second was much later, about 1980, that rerouted the web run in the slitter section from horizontal to vertical. A vertical slitter section allows operator access to move and change slitters without breaking the web down. Note that there also was an alternative web path, called the front drum wrap, that had minor popularity for a while but has been largely obsolete except in tissue (rubber and textiles). About this time we also saw many different options for spreading the individual cut lanes so that the rolls did not interweave as much on the winding set.

Winders are mechanically different from paper machines in several different ways. Winder speed design speeds are typically about 3 times faster than paper machine. This is necessary because winder is a stop-start operation and must run faster to make up for the time when it is stopped because it is common for one winder to process the entire production of one paper machine. High speed operation, well over 2,500 mpm, requires extreme attention to roller balance, framework design and other areas to avoid excessive vibration and possibly throwing a set of rolls from the winder [4]. Another is that roller alignment standards are higher on a winder. The most common standard you find quoted is level and square to less than a hairsbreadth (0.005" or 125 microns). Finally, unfortunately, the much higher degree of man-machine interaction results in more injuries and deaths on the winder than almost anywhere else in the pulp and paper mill complex. The most

common serious injuries are during the (sometimes automated) set change and during front drum splices.

Control distinctions must also be recognized. First, not only is winder motor control more complex than any other motors in the paper mill, they are more complex than almost all (force controlled) motors in *any* industry. If the builder, integrator or mill drive engineers are not suitably experienced with this unique challenge, the results could be increased web breaks, roll interweaving and other defects, particularly during speed changes. Second, while winder controls has setpoints just as the paper machine does, the winder also has setpoint *functions*. By this I mean that all of the TNT's might be varied smoothly and continuously and automatically as a function of roll diameter. In times past this was done by pneumatics and cams. Now it is done by curves stored in industrial computers called PLC's (Programmable Logic Controllers). Picking the right curves for any grade or defect has been the subject of much discussion, often not very helpful. Winder builders have given us very capable controls, but not the heuristics on what to do with them beyond what has been long taught general rules.

Nowhere is the control complexity better illustrated than in rider roller nip programming. As was seen in Figure 3, the weight of the roll makes up part of the total nip on the drums. If left uncontrolled, the nip due to roll weight would then vary from little to big during the winding cycle. There are three problems with this. The first is that at the start of the winding cycle, the nip at the core may be so little as to not be able to pull the web tension without slipping on the drums. Second, even if the web did not slip on the drums the low nip load might make the roll too soft at the core and cause issues at the customer such as telescoping. Finally, winding tight over loose is bad roll structure and can cause certain types of starring. There has been a long evolution of rider roll curves to work around the limitations of uncontrolled roll weight. The current standard curve is back calculated from what amount of rider roll load would be required to make a constant back drum nip throughout the winding cycle. This calculation is strictly statics and is based primarily on roll weight and trigonometry. This 'optimum' curve is shown in Figure 3. When I say optimum it must be recognized that for specific defects, such as the nip-induced crepe wrinkle, this curve would not be ideal. In this particular defect case you would definitely want to reach minimum rider roll load before the lowest diameter at which crepes were found. This illustrates the risk of over-generalizing rules for curves. A better approach is to let the wound roll 'tell you' what is best for a particular situation.

The two-drum winder is an absolutely essential machine in the paper industry. It is productive, sturdy and requires only a modicum of maintenance. However, it has a major limitation for certain applications, namely the winding of large diameter rolls of delicate grades such as LWC and SCA. With these and other grades the ever-increasing weight of the large winding roll on the drums could cause nip-induced defects, such as crepe wrinkles or any of the many tight defects. Several recent design workarounds include pressurized air applied in the winding pocket to

'relieve' some of the roll weight, soft rubber (compliant) drum covers and belted winders. While these designs *may* increase the application range, it is done at enormous cost, complexity and risk. Furthermore, each of these workarounds exacerbated other serious winding problems, such as air bubble wrinkles in the wound rolls on the pressurized system and vibration to the point of set-throws with the compliant designs. Thus it is not clear at this time whether these new designs achieved a net economic benefit even though perhaps a hundred of these 'modern' two-drums are in the field. What is clear is that dozens of mills have taken them out after they had proven themselves too troublesome and that scores of other mills are buying these technologies as upgrades or as part of a new winder. The net effect is that the ever-increasing demand by end-used customers for wound roll size drove designers to find a way to better control nip load. This winder type is called a duplex winder.

Duplex Winders

Duplex rewinders, shown in Figure 9, are named such because every other roll across the width of the set is wound on the opposite side of a drum or central roller(s). In the paper industry these machines are several times as expensive as the two-drum AND only half as productive. So while the entire production of most paper machines can be served by a single two-drum, it takes two duplex winders to do this. Not only are duplex winders costly to buy and operate, they are also costly to maintain because the parts count is much higher. Just as two-drums had two web paths, vertical and horizontal, so do duplex winders. Most of the newer and bigger duplex winders route the webs through the basement and that presents a number of additional design, mechanical, maintenance and operational challenges.

So why would paper mills bother with such expense? The answer primarily comes from customers in one grade; LWC (light weight coated) used for high volume glossy magazines and other high end graphics. Here, as everywhere, the customer wants ever-larger wound roll diameters (and sometimes width) rolls to increase their productivity because it reduces the number of roll changes. Unfortunately, the weight of LWC rolls much larger than 1 m in diameter is enough to generate a number of (mostly tight) defects as well as the debilitating crepe wrinkle. Thus, the paper industry version of the duplex winder takes part of the part of weight of the winding rolls on the drum and the remainder on the core as seen in Figure 9.

Unfortunately, the ability to build quite large rolls on a duplex winder led to a different problem. Just as excessive weight can be trouble due to nips at the outside, namely by generating crepe wrinkles near the outside, excessive weight born on a core led to crepe wrinkles at the core, more commonly called core bursts. Thus, large defect free rolls could be wound, but not safely unwound because all of the weight sits on the cores of the customer's unwind. The customer exacerbates the problem they generated in the first place, by requiring large diameter rolls, by using unwind designs whereby the roll is turned or braked by overhead belts. While overhead belts are more conveniently placed for operators, the 'nip' they impose just adds to the weight born on the core.

Another very serious problem with duplex winders is that the nip between the winding rolls and the drum is exceedingly nonuniform, far more than almost any other application in any other industry. The reason is that the flimsy fiber cores are loaded at the ends and thus bend away from the drum from tension and nip. True, there are rider rolls that can be placed to try to push the bend in the cores flat. However, they are very far from perfect. The result is a quite common tendency to wrinkle at the ends of wide rolls with a symmetrical diagonal wrinkle pattern. This wrinkling lasts until a few tens of centimeters of paper have been added which will then increases the bending stiffness of the system so that it is better able to resist the nip and tension and thus straightens out and levels the nip.

Other Operations Near the Rewinder

There are many other vital operations in and around the rewinder as listed in Table 3.

Table 3 – Other Winder Operations

Core Cutting and Handling – Cores are usually purchased rather than made onsite. (An exception is that cores for toilet and towel rolls are made in the tissue mills.) Furthermore, cores are often purchased full length and must be cut to the specific width of the rolls that are ordered by the customer. Core cutting is almost always done onsite. In summary, full width cores from a nearby supplier are stored in the warehouse, move to the cutter, are then moved to the winder area and finally inserted into the winder during the set change. One major consideration is moisture control as wet cores can dry out in storage inside a roll causing the bottom of the roll to get loose. Also, changes in moisture can result in the cores not matching the width of the roll. There are approximately 100 articles written on cores.

Slitting – While there are many ways to slit, most paper webs are cut with a shear slitter. (An exception is some tissue is cut with score slitters, something like a pizza wheel cutter.) A shear slitter is composed of two slightly overlapping rotating blades and operates in principle similar to a shears (scissors) from which its name is taken. Clean slitting, meaning no dust or fuzz on the roll edges, is essential for many customers most especially those who print. Good slitting requires precision design, maintenance and setups of the two blades. Slitting is also an operational nuisance and productivity challenge because order changes require frequent moving of the blades. Most blade moves are done manually though there are a number of automatic (industrial computer) slitter positioning systems that take orders from production software. Slitters are among the most delicate and precise pieces of equipment found in paper machines. There are about 100 articles written on shear slitting.

Spreading – Slit lanes must be separated. Nowhere is this more critical than the two-drum winder because lanes that overlap result in stuck or tied-up rolls that must be pulped. Also, insufficient separation will also risk dishing on wide winders. Too much or inconsistent separation can also be a problem because it is one cause for rough roll edges. A 1 mm gap between rolls is often considered ideal for two-drum winders. If the minimum roll width is wide, say more than 0.25 meters, a single element spreader such as an after slitter bowed roller or d-bar (newsprint) may be adequate. Narrower rolls, however, require dual element spreaders. All of these are after-slitter spreaders. Some machines employ a before-slitter spreader to assist with spreading. Another even more important roll of before-slitter spreader is to flatten the sheet because even the slightest pucker going through the slitters will ruin roll width tolerances. There are about 100 articles written on spreading.

Salvage Winding – A small rewinder, called a salvage winder, can process a single roll produced on the main winder to edit out certain defects, splice together material to make a full sized roll and to clean up roll edges. A salvage winder is also very useful for inspection and trials. Note that in the converting industry the salvage winder is called a *Doctor* winder after an ubiquitous model name by a dominant builder. More and more mills are abandoning their salvage winders and re-pulping defective rolls instead.

Spool handling - Parent rolls from the reel are typically moved down rails to the unwind of the winder. These rails usually have multiple storage locations in between that serve as a buffer between continuous (paper machine) and discrete (start-stop rewinding) operations. Alternative storage on the floors is clumsy and only used when there is no rail storage. Expired spools are taken from the unwind, stripped of paper, and returned to the primary arms of the reel. This is usually done manually with a crane but complete closed-loop automatic handling of parent rolls and spools is common enough. Sometimes the storage positions are equipped with a 'Sunday drive' that slowly rotates the parent roll to keep it from sagging and thus getting out-of-round.

Wrapping - Wrapping of rolls is almost always required except with some industrial grades of board. The wrapping serves to protect the bilge and ends of the rolls from handling damage and the ravages of environmental moisture. The most common wrapping materials are: plain kraft, wax coated kraft (now most obsolete), poly laminated kraft and stretch film. Wrapping machines seldom cause problems with the wound rolls. However, they do break down often and thus block (an industrial engineering term) the two-drum after the small buffer in between becomes filled.

Roll Handling - Dedicated conveyors with an assortment of other devices are the most common way to get the rolls from the wrapper to the warehouse. The last move of a wound roll is usually made with forklifts equipped with clams. Excessive clamp pressure is a very common way to put a roll out-of-round that then causes speed-limiting issues at the paper mills' customers. Winding tighter will help a little. However, the remainder of the remedy must come from attention to the clamps and other handling equipment and storage.

Warehousing - Rolls are typically stored on ends in stacks up to 10 meters high in an (typically) unheated warehouse. Storage on ends is less problematic than storage on the bilge that will always put a roll out-of-round to some extent. There are many defects that can result from storage due to handling, moisture and mere roll weight. A major safety concern with warehousing is fires. Paper rolls that catch fire will burn through the outer layers that will then snap from tension and scatter fire even further.

Shipping - Rolls are again moved by forklift from the warehouse to either a semi-truck or to a railcar. They are unloaded similarly at the paper mill's customers. Roll appearance always looks much worse after shipping than was seen prior to wrapper. This causes claims and investigations into who or what was responsible. One recent development is to place a multi-plane accelerometer and recorder inside the core of a roll. When the recorder is removed by the customer, it can be hooked up to a PC and so that a time trace of impacts can be played back, something like a seismograph that is used to monitor earthquakes. The time at which large impacts were sensed can be traced back to who had the roll at that time and what the operation was that caused the impact.

Automation and Productivity

Each of the winders in a paper mill has benefited from the PLC and computer control revolution, some far more than others. PLC's or Programmable Logic Controllers, began replacing relays in the late 1970's. They had three distinct advantages. The first was reliability because relays had moving parts that were not always as mill-duty as were industrial controllers. The second was capability, meaning that far more complex logic could be written. The third was the ease of changing a program. However, it took another decade or two for industrial hardened PC's or Personal Computers to be reliable enough to be mill-duty. PC's are better suited for production order handling, slitter positioning and operator interfaces than PLC's. Also in parallel was the need for communicating between possibly dozens of different types of controllers in the paper mill. A last innovation was peculiar to drives when they became digital in the late 1980's. Some of the very high-end systems can do data acquisition at rates exceeding 1,000 samples per second and doing it simultaneously on hundreds of motor parameters and recording it in a circular buffer. Drive tuning and troubleshooting was thus greatly improved

with by the digital revolution and particularly with high-speed data acquisition. That is not to say that that PC's or PLC's could not also do data acquisition. It is just that these are far slower and clumsier to set up than digital drives.

The reel has seen the least automation being largely unchanged for more than a century since Elmer Pope of MacMillan Bloedel invented the automated reel spool change as we now know it. Two rare exceptions to this stasis have emerged. The first mentioned earlier is that the Beloit TNT and the Metso Opti-Reel required levels of PLC and drive control that exceed most anything else found in the pulp and paper complex. The second is for roll length and roll diameter control. In the past, someone had to calculate the approximate size of the parent roll necessary to make an integral number of sets of finished rolls that would meet the diameter range required by the customer. While this can be done with a simple program, it is not something that an operator would be able to do. However, there are complications that confound this simple calculation. The first is that the calculation depends on effective caliper that will vary with each grade. A second is that waste or damaged material at the bottom of the spool might not be consistent. A third is the amount of material stored in a roll depends slightly on how tightly it is wound, especially on the rewinder that has more control over tightness than does the reel. Finally, an upset, such as a web break, will result in a variable amount of loss of material. In the early 2000's *reel optimization* programs that do the nominal calculations for the operator as well as 'learn' how close it gets by monitoring diameters and footages at both the reel and the rewinder and adjusting the parent roll accordingly. The result is fewer finished roll splices. It also reduced waste on the winder as many customers will not allow a splice within a certain distance of the outside of the roll and some do not allow any splices. Not surprisingly, reel optimization not only reduced waste on the spool, it also increased efficiencies on the winder.

Between the reel and the rewinder we see many new options for spool and parent roll handling. For decades extended rails would allow buffer storage and easy movement of the parent roll from reel to rewinder without the need for a crane. Still, the slabbing off of waste at the bottom of the expired spool and movement of the bare spool back to the primary arms was done by an operator and a crane respectively. Now, all of this can be done automatically so that the spools move in a continuous circuit from reel to rewinder and back to reel without the need for an operator.

The two-drum has seen the greatest level of automation efforts. Recall that a single winder can have difficulty keeping up with the output of a single paper machine. This is because though the winder may have a top speed of 2-3 times that of the paper machine, it is a start-stop operation while the paper machine is continuous; making something of a tortoise and hare type of race. Add to this inconsistencies between operators in how long it takes them to manually change out a set of rolls and you have the possibility that a paper machine might occasionally need to be slowed due to a production bottleneck at the winder.

The first automation was to merely have a PLC do the pushbuttons for the set change steps. These steps include automatic stop to finishing roll diameter or length, raising the rider roll (even before the winder reaches a dead stop), unchucking, cutting the tails, ejecting the finished set, injecting a new set of cores and so on. However, while this half step did speed things up slightly, the operators still needed to do tail taping and this mix of manual and automatic functions was limiting and possibly risky. In the 1980's we saw the invention of set change equipment that could attach the tails to the cores so that set change could be done without operator involvement with two exceptions. The first was that a new spool required an operator rethread so that one in every three or four set changes would be mostly manual. The second was at web breaks where several operators are needed to do a splice on the finished roll.

Another area of automation on the rewinder is slitter positioning. It takes about one minute to move one slitter. If a setup has 5-20 cuts, it can take some time to setup for a new mix of widths. With just-in-time and Lean programs becoming more common in paper mills, the grade changes become more frequent, sometimes as many as several per shift. Thus in the 1980's winder builders and slitter manufacturers began developing computer positioned slitters. It would pull production orders in the correct sequence and calculate when and where to move the slitters between sets.

Other automation is also found near the winder. Core cutting and core handling from the cutter to the winder used to be manual, now it can be partly or completely automated. Core insertion into the winder is also commonly automatic. Production sequencing, order tracking, defect tracking and label printing are almost always completely computerized.

With all of the options for winder productivity, it might be difficult to determine how much is needed to keep up with the paper machine. The rule of a single winder running 2-3 times as fast as the paper machine was not adequate as options proliferated and grades became more varied and grade changes more complex. Thus in the 1980's winder builders began to develop 'time cycle' calculations to predict how much winder was needed in a new mill or how much winder upgrade was necessary for an old winder that fell behind a paper machine that had been sped up. This calculation can be done manually but is better suited for spreadsheets [8].

To understand the deterministic part of this calculation we can look at a nominal speed versus time plot as shown in Figure 10. Every set but the last has the following sequence: change rolls, accelerate, run, decelerate in a repeating cycle. The last sequence is similar only that we now must add parent roll change as well as threading. The durations of each of these elements is known by experience, or can be measured or calculated. For example, a manual set change might take 1-1.5 minutes depending on whether the winder is shafted or unshafted respectively. (Fully automated set changes can now perform this step in about 0.5 minutes.) Other stochastic operations not shown here might include slitter setups (1 minute

per blade manual or 30 seconds total for automatic slitter positioning), web breaks (15 minutes to clean up and splice) and so one.

There are two calculations that are done given these inputs. The first is how much time is spent at run speed. This is back calculated by the difference between finished roll length and the length required by the acceleration and deceleration. The second is the average speed of the winder. This is simply the total length of the finished rolls in a single parent roll divided by the total time it takes to run all of the sets in that parent roll. A final safety factor is needed for inevitable operations that are not listed above such as maintenance and for cases where the winder may experience a rash of troubles such as web breaks. Here a common practice is to allow 4 hours a day for these extra troubles, call it a safety factor on productivity if you will.

So now it is possible to calculate whether a proposed or existing winder would be sufficient to keep up with a paper machine. If not, you could do 'what if' scenarios for rebuilds or upgrades. If, for example, slitter changes were frequent we might automate them. If, for example, the caliper was thick and roll diameter small so that set change time became a significant portion of the total time, we could automate set change. You could also compare the cost of adding 10% more productivity of one option versus another versus slowing down the paper machine for those particular conditions.

Profile and Moisture

If there were two areas of paper manufacturing that gave winders more trouble than any others it would be profile and moisture. *Profile* is a general term meaning 'the variation of ___ across the width' of the sheet. Initially ___ could be anything, allowing for troubleshooting of problems to begin based on known patterns. For example, wrinkles on the back side would have a tapered shape and is not compatible with the ubiquitous smiles and frowns found on most components. Similarly, a (narrow) baggy lane could not be caused by an improper value of crown on a calender roller but could be caused by poor grinding or wear on that same calender roller.

However, the biggest profile problems are related to caliper and moisture and bagginess; all of which could potentially have the root cause of a caliper variation. What web handlers and winder people know is that the level of caliper variation that could cause runnability issues on the winder or in end use is often below the threshold of measurement sensitivity of the test lab and far below what might be the capabilities of the online scanner. The reason is that web-based measurement must be able to resolve the couple of percent variation of a sheet that may be only the thickness of a human hair. However, the winder, especially surface winders because of their nips, will easily pick up the affects of the accumulation of hundreds or thousands of layers that build up unevenly in the wound roll. This has led to a lot of finger pointing as the winder operator says the paper is uneven and the papermaker says it is not measurably so and is within spec anyway or that they are doing the

best they can. To summarize a very complicated issue; the winder is usually the fussiest customer of caliper profile AND the most sensitive to caliper variation [2].

Another area of trouble for the winder is moisture. Obviously, moisture profile (i.e., variation across the width) can be a problem. Baggy lanes cause troubles for both winders and printing presses and bagginess might be caused by a moisture streak. Also, many cases of interweaving on a two-drum winder (occurring after the challenging start and acceleration) are caused when a moisture streak on one side of a lane causes it to steer into its neighbor. However, nominal moisture levels can also be a problem [9]. If the paper is wetter or drier than equilibrium with the environment, the winder may have trouble during the set change. It takes on the order of one minute for the paper exposed on both sides to equilibrate with the environment; far too long for the moisture to change when the winder is running at speed. However, when it stops it has plenty of time to take on or give up moisture. The growth of the sheet can cause offsets in the wound roll that is called a splice offset. Worse yet is shrinkage of a wet sheet because it will contract sideways against the slitter blades and tear the sheet, causing a web break as the winder starts. Other problems with changing moisture include loose cores, wrong core length and performance variation at the end-use customer. While there are many factors that drive the selection of a nominal moisture in paper manufacturing, it is quite clear what will perform best at the winder and in the pressroom: in equilibrium with those environments, or about 5% by weight in a 50% RH room.

There are a couple of other paper manufacturing factors that have great affects on the winder and end-use customers. The first is called *fiber angle* by papermakers but is known in mechanics as skew. Here, the principle axis of the material does not align with the MD. This crookedness, which can be as much as 5-10 degrees, makes the material prone to wrinkling, chiral curl and other problems. The second is coefficient of friction. If the web-web COF is too low, such as coated food board, the rolls are prone to telescope during winding and especially during unwinding at the customer. If the web-web COF is too high, such as with book, NCR and sack-kraft paper, then the winder may experience speed-limiting vibration or even set throws. COF also has a very large factor in the propensity to nip induced defects such as crepe wrinkles on newsprint or LWC grades.

The Paper Mills' Customers

Paper is used in an uncountable number of ways, so it is difficult to capture the scope here. However, the major end-use applications by volume include printing (newsprint and magazine), sheeting (for sheet fed printing presses and office copy/printer paper), boxes (flat or corrugated) and tissue (bath, facial and towel). Even despite the extreme diversity of products and customers, there are a number of common customer complaints as listed in Table 4.

One of the oldest metrics of customer complaints is web break rate in the newsprint market. Here the customer will count beaks and forward the break rate back to the suppliers and compare them with their competitors. There are two major problems

with this simple metric. The first is that the sample size is usually not sufficiently large to be statistically meaningful. It may take as many as 10,000 rolls to distinguish performance between two suppliers [10]. Furthermore, some of most of the variables affecting (web break) performance are owned by the customer. One example is merely the humidity of the pressroom. Another is the mechanical and control condition of the equipment. What is surprising to those who have been in both paper mills and pressrooms was that presses often lacked design and maintenance care that was expected on upstream equipment. One example is optical alignment of every roller. Another is load cells to monitor tension. Registration issues are similarly cloudy as to whether they belong mostly to paper manufacturing or mostly to mechanical and control conditions on the printing press. While things are modernizing in the printing press design and operation, it does not bode well for paper mills to have customers who are sometimes weak problem solving partners.

Table 4 – Common Customer Complaints

Bagginess – a paper machine issue
Printability – a paper machine or product design issue
Registration – a paper and printing machine issue
Roll Defects – see Roll and Web Defect Terminology
Tension Control – a variety of issues with both roll shape and unwind condition
Wrinkles – can be caused by poor paper or by poor customer equipment condition
Web breaks – common problems with news and LWC that have a complex set of causes

Learning More About Winding

Winding is one of the oldest and best documented of the web handling sciences. Six books, about 1,000 articles and about 10,000 patents cover this area quite well with few exceptions. Indeed, there is the possibility that there may be too much written material so that can be hard to quickly find what you are looking for. This is especially true since Internet searches are almost certainly going to be worthless as the words wind, winder and winding are used for many things well outside of coiling of paper webs [1]. Furthermore, it is quite easy to get lost in the details and lose context.

So what would I suggest for those who might want to learn more? The first is to obtain one or more books on the subject. I have listed them in Table 5 ranked in order of general importance. However, a much faster way to jumpstart this process would be to take a two-day short-course on the subject.

Table 5 - Books and Related References on Winding and Winding Machines

1. Roll and Web Defect Terminology by Duane Smith 1995, 2007

2. Winding Machines, Mechanics and Measurements Dr Keith Good and Dr David Roisum 2007
3. Anthology of Winding by Jan Gronewold 2000
4. Winders the Complete Guide by Jan Gronewold 1998.
5. The Mechanics of Rollers by David Roisum, 1996.
6. The Mechanics of Winding by David Roisum 1994
7. Web Machine Buying Guide by David Roisum 2010
8. Winding by Ken Frye 1990
9. TAPPI Finishing and Converting Conference Proceedings 1975-2005.
10. International Web Handling Conference Proceedings 1986-Present

Finally, one can learn from winder builders. The oldest and largest of the paper machine sized winder builders are given in Table 6.

Table 6 – Some of the Largest Winding Machine Builders

1. Beloit – Beloit Wisconsin USA (bankrupt in the late 1990's)
2. Black Clawson – Fulton New York USA
3. Jagenberg/Voith - Heidenheim Germany
4. Metso – Järvenpää Finland

Table 7 – Abbreviations used in this section

CD – Cross Direction (XMD or TD also used in other literature)
LWC – Light Weight Coated paper
MD – Machine Direction
PLC – Programmable Logic Controller
SCA – Supercalendered (the A designation is for brightness)
ZD – Z Direction

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Figure 1 – Classes of Winders

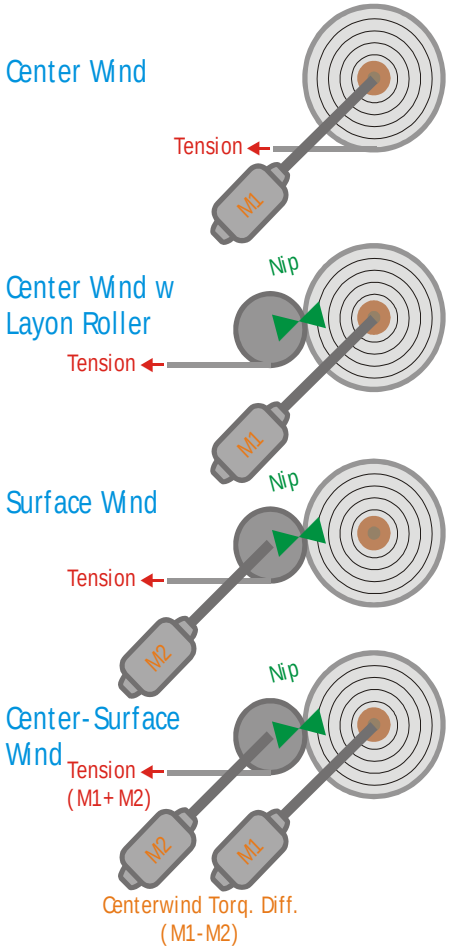

Figure 2 – Range of Tightness Covered by the Different Classes of Winders

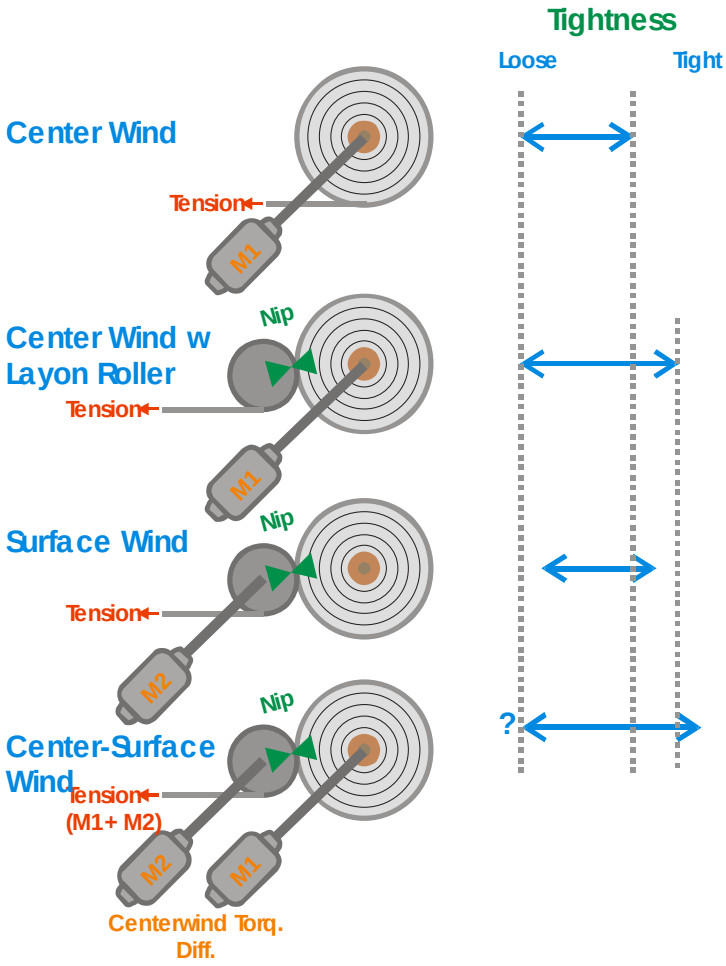

Figure 3 – Nip Control Program for Winders

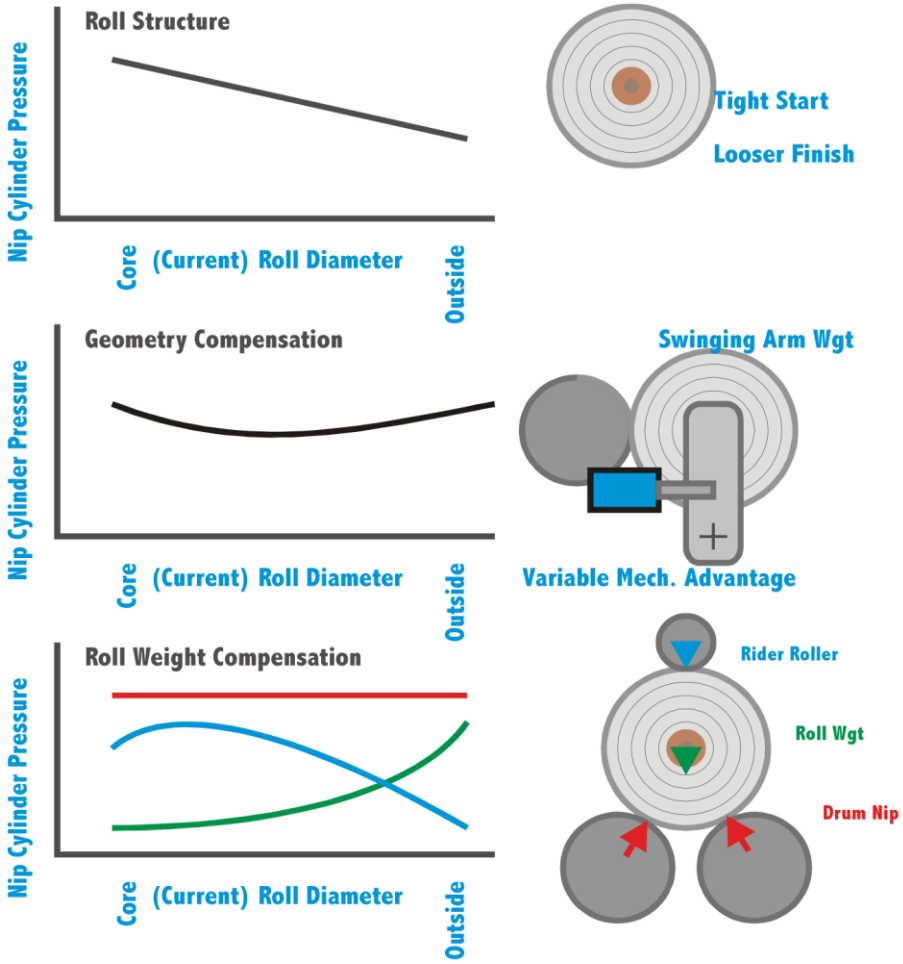

Figure 4 – Stresses Inside a Wound Roll

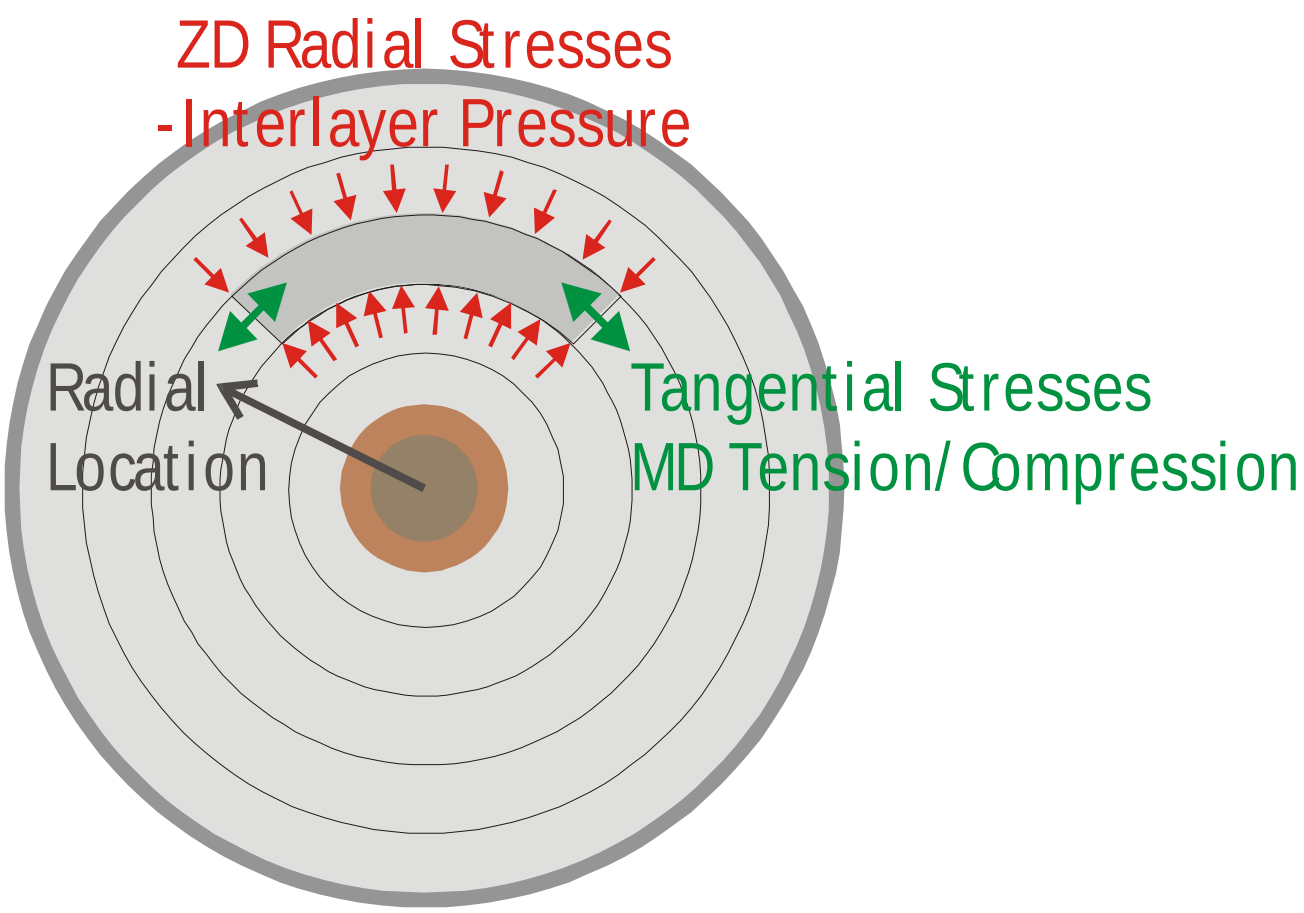

Figure 5 – Interlayer Pressure Inside a Wound Roll

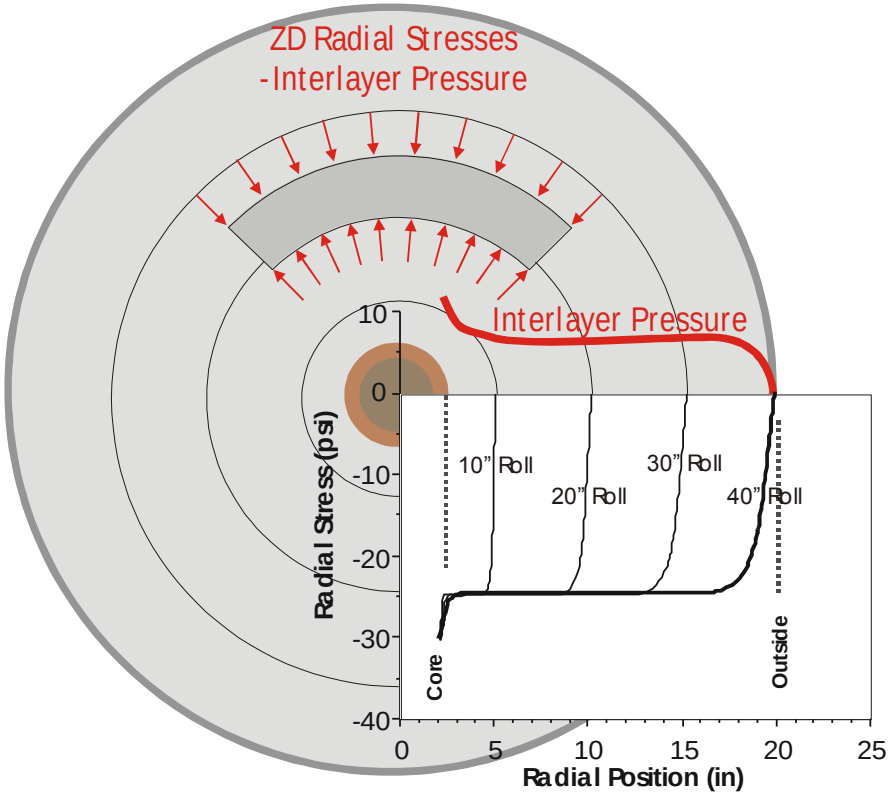

Figure 6 – The Reel

Figure courtesy of Metso.

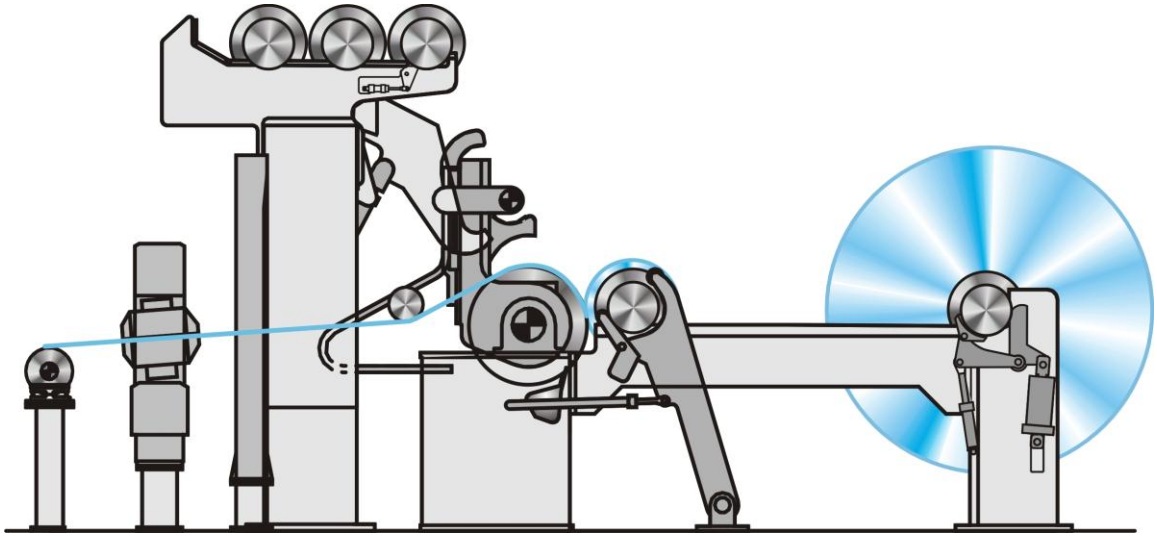

Figure 7 – Variation of Nip Load on a Reel as a Function of Time

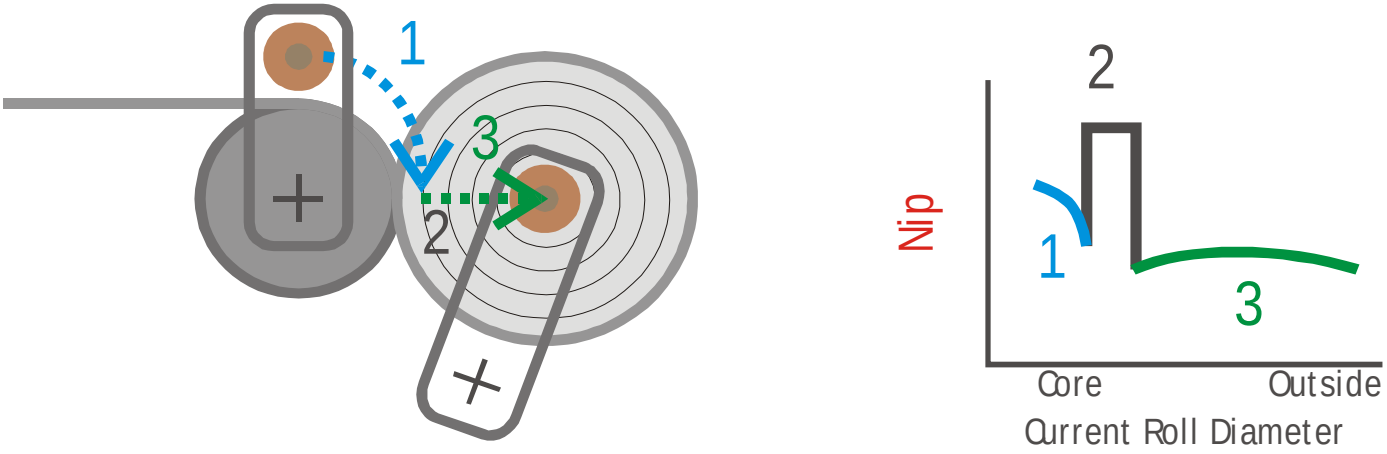

Figure 8 – Two Drum Winder with a Vertical Slitter Section

Figure courtesy of Metso.

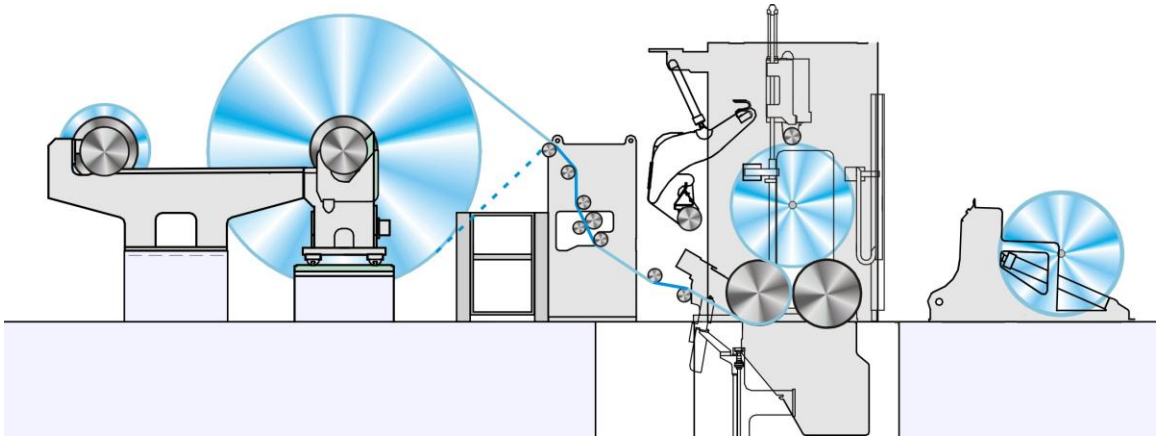

Figure 9 – A Duplex Winder

Figure courtesy of Metso.

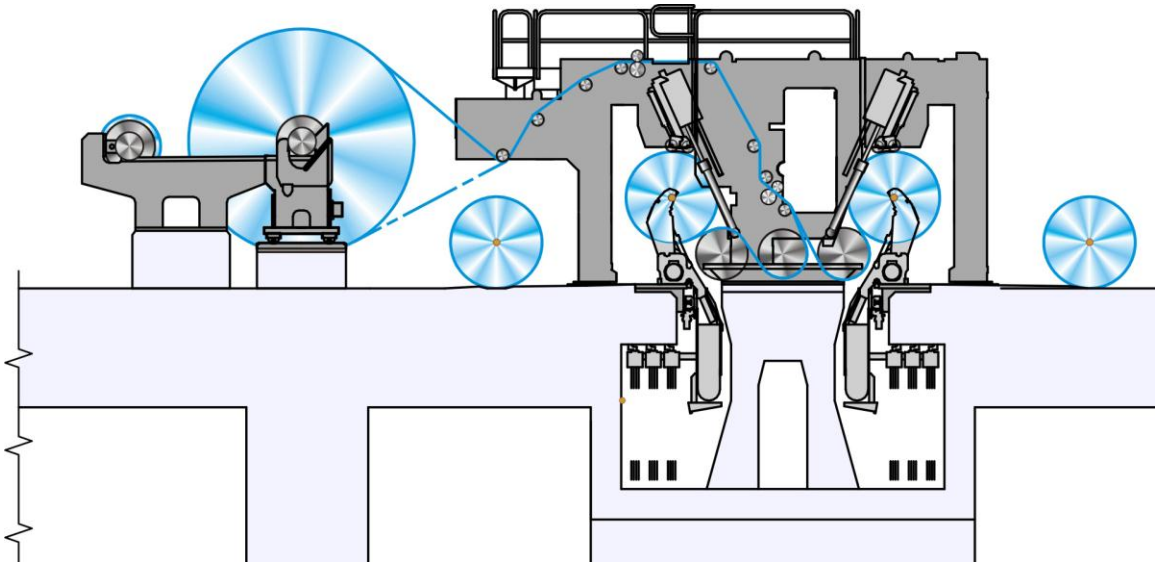

Figure 10 – Winder Productivity: Speed versus Time Plot